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A novel strengthened dispersed particle gel for enhanced oil recovery application

Caili Dai[a], Wenxia Chen[a], Qing You[b], Hong Wang[b], Yang Zhe[a], Long He[c], Baolei Jiao[c], Yining Wu[a,*]

[a] School of Petroleum Engineering, State Key Laboratory of Heavy Oil, China University of Petroleum (East China), Qingdao, Shandong 266580, People's Republic of China
[b] School of Energy Resources, China University of Geosciences, Beijing 100083, People's Republic of China
[c] Petroleum Engineering Institute, Northwest Branch of Sinopec, Urumchi 830000, People's Republic of China

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ABSTRACT

A novel strengthened dispersed particle gel (SDPG) was proposed and investigated to improve high-temperature and high-salinity stability of foam, which uses silica nanoparticles as reinforcing material to support the inner framework of particle gel. In this paper, SDPG was successfully prepared and applied to a new three-phase foam system (STPFS). Indoor experiments were conducted to evaluate the salt tolerance, thermal tolerance, plugging capacity and enhanced oil recovery capacity of the STPFS. It proved that silica nanoparticles could improve the high-temperature and high-salinity stability of the gel particles effectively. Consequently, the new three-phase foam system (STPFS) exhibited superior salt and temperature resistance, with a salinity of 80,000 mg/L of Na^{+}, 15,000 mg/L of Ca^{2+} and Mg^{2+} and temperature tolerance of 110 °C. In addition, core-flooding test indicated the STPFS possessed better plugging capacity with a resistance factor of 310 and better enhanced oil recovery capacity with the oil recovery increment of 26.79% under high temperature (110 °C) and high salt environment (212,633.8 mg/L).

Introduction

Water cut of oil well is a problem that cannot be avoided during oil exploitation. How to control water cut has been increasingly serious issue. Due to the heterogeneity of reservoir, fluid flow, the difference of fluid mobility and other reasons, it is easy to form water advantage channel, leading to water cone, water channeling, fingering and causing water flooding inefficient finally [1–3]. To decrease water production, several chemical methods including polymer flooding, injecting foams, particle system, gel system have been widely applied in oil field [4–9]. Among these, foam has been successfully used in mature reservoirs due to its selectively plugging capacity, easy preparation and superior profile control capacity [10,11]. However, foam is unstable during transporting in porous media, especially in high temperature or high salinity reservoirs. Therefore, the stability of foam has become a serious problem which limits its extensive application in oilfield.

To improve foam stability, many additives have been reported, including polymers, polymer gels and particles [12–15]. Polymers with high viscoelasticity increase the elasticity of liquid membrane between bubbles and form a shell to prevent Ostwald ripening, thus improving foam stability [16,17]. However, the viscosity of polymers decreases with the increase of temperature, which leads to low stabilization of foam in high temperature. A new foam system, called three-phase foam system made up of gas, liquid and particles has been paid much attention. Compared with general gas-liquid two-phase foam, the three-phase foam consists external solid phase to stabilize foam and gets better performance in profile control [18]. Inorganic particles as foam stabilizer have been studied, considering their ability absorb on gas–liquid interface to decrease the drainage speed of liquid [19–21]. However, the adsorption of surfactant on solid particles which always changes the wettability of inorganic particles, which makes particles difficult adsorb on gas–liquid interface and therefore decreases foam stability [22].

In the recent few years, dispersed particle gel (DPG) has been widely used in deep displacement [23,24], which is characterized as simple processing, low cost, strong shearing stability, and being

* Corresponding author. Fax: +86 532 86981161.
E-mail address: wuyining@tju.edu.cn (Y. Wu).

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environmentally friendly [25–28]. Meanwhile, the gel particles with viscoelasticity can stabilize foam. In order to improve foam stability and plugging ability, the combination of foam and DPG together has been investigated in our previous studies [29,30], which showed good performances. But the capacity of traditional DPG to stable foam is limited at high temperature. It will dehydrate at the process of transporting, causing a weakening of foam stability. To improve the stability of gel, the study of coal fly ash (CFA) as a reinforcing material for polyacrylamide (PAM)/ polyethyleneimine (PEI) composite gels has been reported and has showed positive impact on gel strength and morphological properties [31]. The previous works provide the impetus for studying particles as a reinforcing material for gel systems.

In this research, the researchers focus on developing a novel strengthened dispersed particle gel (SDPG) using silica nanoparticles (SiO_2) as reinforcing materials to improve the high-temperature and high-salt stability of gel particles. The SDPG was added into surfactant solution to form foaming agents. Temperature resistant property, salt resistant property, plugging ability and enhanced oil recovery capacity of this system were studied. Finally, enhanced oil recovery mechanism of this novel foam system was analyzed.

Experiment

Materials

The non-ionic polyacrylamide (PAM) with an average molecular weight of 9,650,000 g/mol and the phenolic resin crosslinking agents were both provided by Yuguang Co., Ltd., Dongying, China. Sodium dodecyl sulfate (SDS, anionic surfactant) and silica nanoparticles (15 nm) were purchased from Aladdin Reagent Company. NaCl, $CaCl_2$ and $MgCl_2$ were purchased from Sinopharm Chemical Reagent.

The crude oil sample from Tahe oilfield with a density of 0.7593 g/cm^3 and a viscosity of 1.728 mPa s at the reservoir temperature of 110 °C was used for the displacement experiments.

The formation brine of Tahe reservoir was used for all experiments, which was prepared with deionized water. The compositional analysis of the formation brine is shown in Table 1.

Preparation of bulk gel

The traditional bulk gel solution was prepared by mixing 0.6 wt % PAM and 0.6 wt% phenolic resin crosslinking agents in brine water using our own method [32].

The strengthened gel solution was prepared as follows. Firstly, 1000 g of brine water was added into a beaker then added 6 g of polyacrylamide after stirring for 4 h. Next, drop a series of concentrations of silica nanoparticles in the range from 0.1 wt% to 0.5 wt% separately into the polymer solutions and stir for 1 h. Finally, put 6 g of phenolic resin crosslinking agents into the above mixtures slowly and stir for 20 min to get the gellant solution prepared. The stirring speed is 200 rpm in this experiment.

The prepared samples were put into an oven at 110 °C to obtain strengthened bulk gel subsequently determine gel strength of different concentration of silica nanoparticles, where the gel strength was determined through breakthrough vacuum measurements, following the procedure in Reference [33].

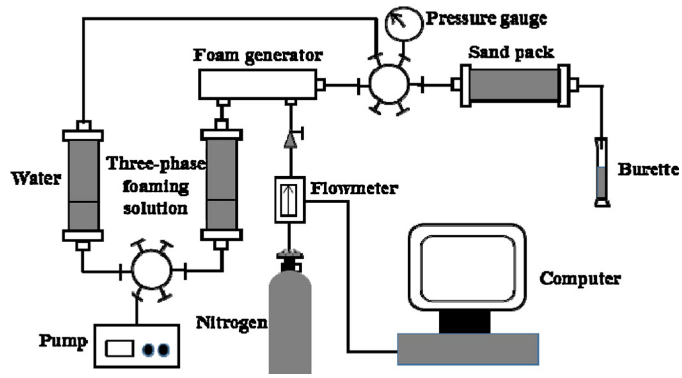

Fig. 1. Schematic of the single sand-pack test.

Preparation of SDPG

Similar with traditional DPG [32], the SDPG was also prepared by high speed shearing method using a colloid mill (JM-85, Shandong Longxing Instruments Ltd., China) by adding 400 g of bulk gel with 400 g of brine water into the colloid mill. After milling for 20 min at 2000 rpm, the particle gel product was obtained.

Scanning electron microscope (SEM) and dynamic light scattering (DLS) measurement

Scanning electron microscope (SEM, JEM-100CXII, Japan) was used to study the morphology of traditional bulk gel and strengthened bulk gel.

To study the shrinking of gel particles, DPG and SDPG were aged from 3 days to 20 days at 110 °C and total salinity of 212,633.8 mg/L. Then a temperature-controlled DLS device (Malvern Zetasizer Nano S) was used to determine the particle size of the aged DPG and SDPG.

Preparation of three-phase foam (N_2 foam)

In the three-phase foam system, the foaming agent used was SDS with the concentration of 0.3 wt% and the aged DPG and SDPG were used as foam stabilizer separately with the concentration of 0.1 wt%. All DPG and SDPG particles needed were aged for 5 days at 110 °C to provide a more realistic simulation of reservoir condition. Foam is generated by Waring blender method. Drop 100 mL mixture into a homogenizer, stir for two minutes, then put the foam into measuring cylinder rapidly and record foaming volume and foam half-life (the time when the system liquid drainage reaches 50 mL), which were used as foam property evaluation indexes.

Plugging capacity test of three-phase foam

The plugging capacity was determined via single sand-pack test. The experimental diagram is shown in Fig. 1. The length of sand-pack was 20 cm and the inside diameter was 2.5 cm. The

Table 1
Composition of the formation water of Tahe oilfield.

Ions	$Na^+ + K^+$	Ca^{2+}	Mg^{2+}	Fe^{3+}	I^-	Cl^-	SO_4^{2-}	HCO_3^-
Concentration (mg/L)	68,748.0	11,874.1	1226.9	9.0	14.0	130,423.5	230.1	108.2
Total (mg/L)	212,633.8							